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Effects of vegetation on runoff generation, sediment yield and soil shear strength on road-side slopes under a simulation rainfall test in the Three Gorges Reservoir Area, China

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HIGHLIGHTS

- Vegetation recolonization was essential in erosion control on roadside slope.
- Grass & Shrub was more suitable on low-volume road for its higher cost-effectiveness.
- The erosion generated on cutslope was higher than that on fillslope.
- Soil shear strength improved by roots was greatly effective in erosion reduction.

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ABSTRACT

Vegetation recolonization has often been used to control roadside slope erosion, and in this paper, four restoration models – Natural Restoration, Grass, Grass & Shrub, Sodded Strip – were chosen to recolonize the plants on a newly built unpaved roadside slope in the Three Gorges Reservoir Area. After eight months growth, eight rainfall simulations (intensity of 90 mm h^{-1} for 60 min) and in-situ soil shear strength test were then carried out to identify the impacts of vegetation on roadside slope erosion and soil shear strength. The erosion on cutslopes was higher than that on fillslopes. The runoff coefficient and soil detachment rate were significantly lower on the Grass & Shrub model (4.3% and 1.99 g m^{-2} min^{-1}, respectively) compared with the other three, which had the highest surface cover (91.4%), aboveground biomass (1.44 kg m^{-2}) and root weight density (3.94 kg m^{-3}). The runoff coefficient and soil detachment rate on roadside slopes showed a logarithmic decrease with the root weight density, root length density and aboveground biomass. The soil shear strength measured before and after the rainfall was higher on Grass & Shrub (59.29 and 53.73 kPa) and decreased on Grass (46.93 and 40.48 kPa), Sodded Strip (31.20 and 18.87 kPa) and Natural Restoration (25.31 and 9.36 kPa). Negative linear correlations were found between the soil shear strength reduction and aboveground biomass, root weight density and root length density. The variation of soil shear strength reduction was closely related to the roadside slope erosion, a positive linear correlation was found between runoff coefficient and soil shear strength reduction, and a power function was shown between soil detachment rate and soil shear strength reduction. This study demonstrated that Grass and Grass & Shrub were more suitable and highly cost-effective in controlling initial period erosion of newly built low-volume unpaved road.

1. Introduction

The Three Gorges Reservoir Area (TGRA) has been affected by the Three Gorges Project and lies on the upper Yangtze River in the central-western region of China. The TGRA covers 79,000 km^2 and has become the world's biggest artificial reservoir. However, in recent decades, the unpaved road network has expanded rapidly because of the Three Gorges Project, tourism development and countryside migration. Soil erosion increased by road construction has become a serious problem in the TGRA because it has deteriorated the water quality and accelerated the reservoir sedimentation.

For a long period of time, steep slope cultivation and land-use and land-cover change had been identified as the biggest sources of heavy soil erosion in the TGRA (Meng et al., 2001; Lu and Higgitt, 2001; Cai

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et al., 2005; Zhang et al., 2003; Liu et al., 2000; Chen et al., 2011). The important role of roads and road construction in soil erosion was rarely accounted for in erosion control management. One of the main impacts of road construction is the creation of bare and steep roadside slopes (Cerdà, 2007; Bochet and García-Fayos, 2004), and the lack of surface protection has generated significant amounts of soil loss on roadside slopes during the rainy season (Bochet and García-Fayos, 2004; Bochet et al., 2010; Jordán-López et al., 2009; Arnáez et al., 2004; Megahan et al., 2001; Megahan, 1978). Severe anthropogenic disturbances and poor soil conditions have made vegetation restoration by natural processes on roadside slopes quite difficult (Bochet and García-Fayos, 2004; Auerbach et al., 1997).

Vegetation cover has been a common method of reducing roadside slope erosion and has been shown to be extremely effective in many areas worldwide (e.g., Megahan et al., 1983; Swift, 1984; Bochet et al., 2005, 2009; Espigares et al., 2011; Cerdà, 2007). Bochet et al. (2009) conducted a research study to determine a method of controlling the roadside slope erosion in a semiarid Mediterranean area in Eastern Spain and indicated that slope type and angle were the key factors in roadside slope soil erosion and plant colonization, with drilling proving to be a promising technique for cutslope restoration and topsoiling followed by hydroseeding with mixed native species seed being a more efficient method on fillslope. Buss et al. (1997) conducted perennial grass experiments on rural roadsides in the Sacramento Valley of California and concluded that non-native grass had a greater advantage in roadside vegetation restoration than native grass species. Grace's (2000) research in Alabama found that erosion mat treatment (seeded with an exotic species mixture and covered with wood excelsior) was better at reducing roadside slope erosion compared with native species and exotic species. In Idaho, Megahan et al. (2001) evaluated three cutslope erosion control treatments, including dry seeding, hydroseeding plus mulch, and terracing with hydroseeding plus mulch; according to data from their four year investigation, dry seeding was the most cost-effective treatment on such slopes with deep alluvial soil.

However, such reports on erosion mechanisms, plant selection and the efficiency of revegetation methods on roadside slopes were rarely conducted in the TGRA. A large proportion of the roads in the TGRA were low-volume unpaved roads, and an erosion control treatment such as hydroseeding was unsuitable in the TGRA because of its high cost. Therefore, cost-effective and locally applicable treatments that can adapt to the rapid development of the road network are required.

In addition to rainfall, the force of gravity has also played a very important role in the increase of roadside slope erosion, especially on the steep cutslopes (Beschta, 1978; Amaranthus et al., 1985; Wemple et al., 2001). The goal of roadside slope revegetation was not just to determine the efficiency of slope surface cover in reducing the rainfall and surface concentration flow affects but also to determine the capability of vegetation in improving the soil strength against landslides and collapse caused by soil strength failure (Nyssen et al., 2002; Valentin et al., 2005; Lammeranner et al., 2005; Sidle et al., 2006).

In this study, a newly built unpaved road was selected as an example of a low-volume road in the TGRA. Four erosion control treatments – Natural Restoration (NR), Grass (GR), Grass & Shrub (GS) and Sodded Strip (SS) – were evaluated on both cutslope and fillslope. The specific purposes of this paper were to describe the surface coverage on the roadside slopes under different treatments, identify the effects of different treatments on the reduction of runoff and sediment based on rainfall simulations, measure the in-situ soil shear strengths before and after the rainfall simulation by a portable field inspection vane tester, collect the aboveground biomass, and measure the plant root characteristics, such as root weight density and root length density, to discuss the impacts of vegetation on runoff generation, sediment yield and the surface soil strength of roadside slopes under simulated rainfall conditions.

2. Materials and methods

2.1. Study area description

The TGRA covers part areas of Hubei and Chongqing provinces. Three studies were conducted in TGRA for road development and management, one in Hubei province and two in Chongqing province, to their specific conditions, respectively. Eight watersheds located in Hubei province were selected for investigations of their soil condition, plants, road information and land utilization. According to the investigations, the dominant plant species were similar and the soil matrix was sand-shale. Orchard and tea garden were widely distributed and a large number of low-volume roads were built among those lands. This study was conducted in Mozixi, one of the eight investigated watersheds, which is located 45 km southeast of Yichang city in Hubei province at approximately 30°37′ N, 111°30′ E and is a small watershed that covers 7.3 km^2 (Fig. 1). The area is in a northern subtropical continental monsoon climate zone and has a mean yearly temperature of 17 °C. The long-term annual rainfall is 1217 mm, which primarily occurs from April to September (>80% of the total rainfall). The elevation ranges from 137 to 675 m. The purplish soil in this region is predominantly weathered from red sand-shale. The main species of trees are horsetail pine (*Pinus massoniana*), Japanese cedar (*Cryptomeria fortunei*) and bao li (*Quercus serrata*), and shrubs are dominated by horseshoe vitex (*Vitex negundo*) and masuri berry (*Coriaria nepalensis*). The grass species are numerous, and bermudagrass (*Cynodon dactylon*) and goosegrass (*Eleusine indica*) are the dominant. The main land uses are paddy fields and orange groves.

The road network in the study area was well developed with a road density of 9.24 km km^{-2}. However, low-volume roads made up greater than 70% of the total road length in the watershed and included unpaved rural roads and grass roads that provided access for farmers and farming vehicles. Unpaved rural roads and grass roads were widespread and accounted for 49.2 km, with a 4.1 km concrete main road made for heavy trucks that zigzagged through the watershed to connect different villages. Roads paved with other material, such as gravel, accounted for 9.7 km. Much of the roads experienced high use, but the roadside slopes were poorly protected and managed, with serious soil erosion occurring frequently from roadside slopes in the rainy season. The results of field investigation of the degree distributions of the roads conducted in August 2009 were shown in Table 1. All of the cutslope sections in the study area were greater than 30°, and the average degree was 42.5°; the degree of the fillslopes was much gentler and averaged 21.2°.

2.2. Plot installation and plant establishment

The road section tested in this paper was located on a newly built unpaved rural road that was finished in August 2009 and built for light motor vehicles. The roadside slopes were shaped on both cutslope and fillslope to achieve an experimental design degree (30°) immediately after the road building was complete. Four 5.0 m long × 2.0 m wide runoff plots were built on both the cutslope and fillslope, and each plot had a runoff storage container of 1000 l. Natural Restoration (NR), Grass (GR), Grass & Shrub (GS) and Sodded Strip (SS) were used to colonize the slope vegetation. The experiment plots and plant restoration models are shown in Fig. 2, the acronyms of the plots set and other parameters appeared in the text were described in Table 2.

The grass *C. dactylon* was chosen to transplant on GR plots at a row space of 10 cm. For the GS plots, the shrub species were 1-year-old saplings of *V. negundo* at almost 80 cm in height and were transplanted at a planting space of 60 cm, and the grass species was *C. dactylon* and was inter-planted in the shrubs. The SS slope revegetation technique combined engineering and biological measures, with grass seeds and fertilizer mixed and fixed on a matrix that is made of non-fabric material and wood-pulp paper that can decompose from weather exposure. In this